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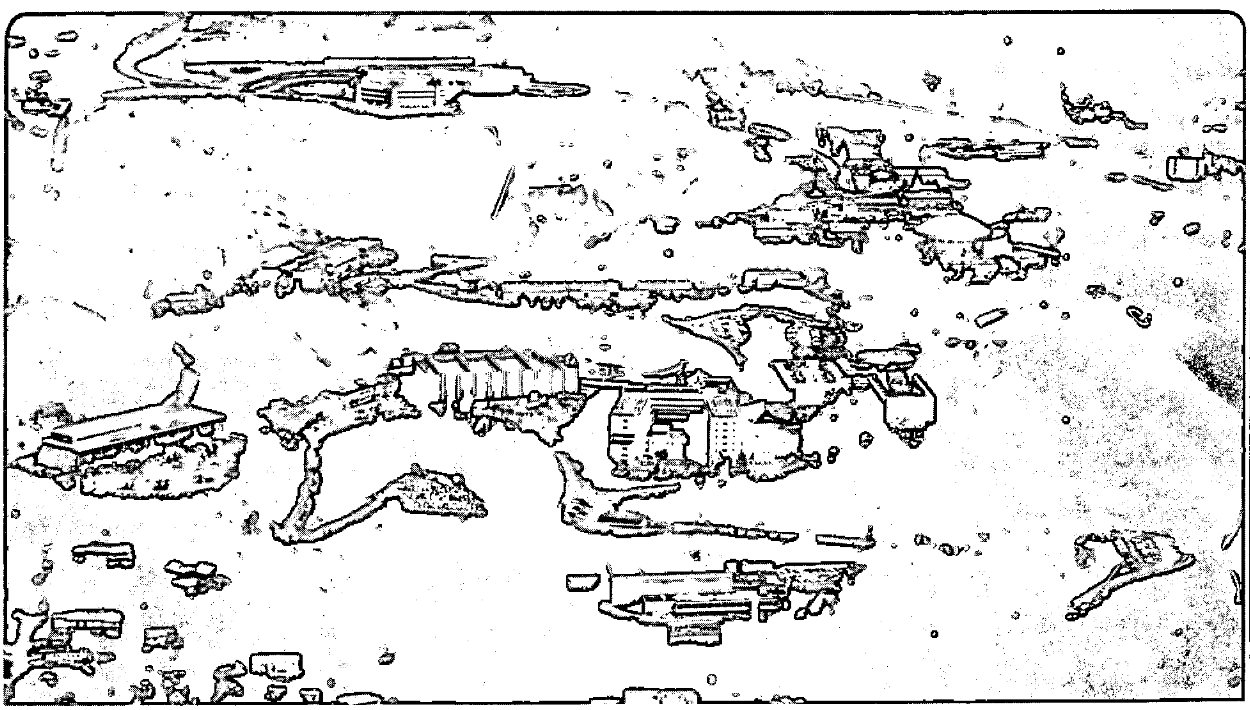

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HELIUM COOLING SYSTEMS FOR LARGE SUPERCONDUCTING PHYSICS DETECTOR MAGNETS

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The large superconducting detector magnets used for high energy physics experiments are virtually all indirectly cooled. In general, these detector magnets are not cryogenically stabilized. Therefore, there are a number of choices for cooling large indirectly cooled detector magnets. These choices include; 1) forced two-phase helium cooling driven by the helium refrigerator J-T circuit, 2) forced two-phase helium cooling driven by a helium pump, and 3) a peculation gravity feed cooling system which uses liquid helium from a large storage dewar. The choices for the cooling of a large detector magnet are illustrated by applying these concepts to a 4.2 meter diameter 0.5 tesla thin superconducting solenoid for an experiment at the Relativistic Heavy Ion Collider (RHIC).

BACKGROUND

Large superconducting detector magnets are characterized by being indirectly cooled with helium flowing through tubes to cool the support shell which in turn cools a lightweight coil made with an aluminum superconductor. An example of this type of coil is the magnet for the Solenoinal Tracker at RHIC (STAR) detector on the RHIC heavy ion colliding beam facility at the Brookhaven National Laboratory in the United States.[1,2] The solenoid, which supplies the magnetic field for the STAR detector, will have a warm bore diameter of 4.4 meters and a length of 6.9 meters. The magnet and its cryostat, which are 0.3 meters thick, must be thin from a particle interaction standpoint so that a calorimeter detector can be outside of the solenoid. The STAR solenoid, which will be less than 0.7 radiation lengths thick, will generate a uniform magnetic induction of 0.5 tesla between two shaped iron poles which will be 6.2 meters apart. By making the STAR solenoid thin, the mass of the return yoke and the size of the STAR experiment is reduced. In order to make the STAR magnet thin from a particle interaction standpoint, the cryogenic cooling system must be selected with care. As a result, a tubular cooling system was selected for the STAR solenoid. This report investigates and compares several different options for cooling the STAR solenoid and other detector magnets which are similar in size to the STAR solenoid magnet. The cooling solutions suggested in this report can be applied to other detector magnets as well.

TWO-PHASE HELIUM TUBULAR COOLING VERSUS BATH COOLING

The superconductor in the typical detector solenoid does not care how it is cooled as long as its temperature is below the critical temperature of the superconductor with some safety margin. Two-phase cooling in tubes can provide all of the cooling needed to keep the magnet superconductor below its critical temperature, and it avoids all of the major problems encountered in any large bath cryogenic system. The advantages of a two-phase helium cooling system for a large detector magnet are as follows: 1) The cool down of the magnet is well controlled because the helium in the tube flows along a well defined path, and the rate of cool down is dominated by the rate of flow of the helium in the tube and the temperature drop from the points being cooled to the helium gas entering the tube. 2) The mass of a two-phase forced flow cooling system is less than the mass of the standard bath cooled cryostat. The radiation thickness of the forced two-phase cooling system is almost negligible. 3) The amount of helium in direct contact with the magnet coil is minimized and all of this helium is within a 10 to 12 millimeter diameter tube. With so little helium in contact with the magnet coil, the helium boil-off during a magnet quench is well controlled, which has profound positive safety implications for the magnet and its cryogenic vacuum vessel. 4) The location of the helium input and output to the magnet and the location of the gas cooled electrical leads is not impacted by this type of cooling system.

The major disadvantage of tubular cooling over bath cooling for cooling a detector solenoid is that the magnet operating temperature is higher for the two-phase cooling system than it would be if the magnet were bath cooled on the same refrigerator. The superconductor in a detector magnet is cooled by conduction from the cooling tube. The temperature difference between bath cooling and tubular cooling is a function of the tube spacing on the outside of the magnet, the thermal conductivity of the path between the tube and the superconductor, and the method of circulating the helium in the magnet cooling tubes.

FORCED TWO-PHASE COOLING

Figure 1 shows a forced two-phase helium system where the pressure is provided by the refrigerator compressor. This method of cooling employs a control dewar and heat exchanger to subcool the helium from the refrigerator J-T circuit before it goes out to the magnet cooling tubes. The advantages of this approach are as follows: 1) The heat exchanger and control dewar shifts the phase of the helium going out to the magnet from the gas side of the two-phase dome to the liquid side, which reduces the pressure drop along the flow circuit at least a factor of two. 2) The control dewar and heat exchanger have the effect of damping out most of the oscillations due to two-phase flow in the magnet flow circuit. The control dewar is a critical element for a two-phase flow system connected to a helium refrigerator. 3) The control dewar acts as a buffer vessel which can provide additional cooling during times when the heat load at the magnet exceeds the capacity of the refrigerator. The major disadvantage of the flow circuit shown in Fig. 1 is that when the refrigerator stops operating, the magnet will warm up. The primary cause of refrigerator shut down is power glitches which shut down the helium compressor.

The flow circuit shown in Fig. 1 is very simple. A coiled copper tube heat exchanger can be built to fit down the neck of a four inch neck 500 liter storage dewar. The gray lines shown in Fig. 1 are the bypass circuit needed to cool the magnet from 300 K to about 10 K and a mixing circuit which allows one to control the temperature of the gas entering the magnet during the cool down. The valves shown with dark centers are normally closed when the system is operating with the magnet at 4.6 K. The valves with white centers are normally open when the magnet is operating at 4.6 K. Gas flow from the gas cooled electrical lead bypasses the refrigerator and is sent back to the compressor intake at 300 K.

Figure 1 also shows a forced two-phase flow circuit where the pressure and flow needed to drive the circuit is supplied by a backup positive displacement liquid helium pump.[3] This method also employs a control dewar and heat exchanger to insure that the lowest possible quality helium enters the flow circuit from the control dewar. The advantages of using a positive displacement helium pump for providing the flow to the two-phase flow circuit are: 1) The liquid helium pump will continue to supply liquid helium to the magnet flow circuit as long as there is liquid helium in the control dewar even if the refrigerator is not working. 2) The mass flow through the flow circuit can be controlled by varying the speed of the positive displacement pump so that large amounts of refrigeration can be delivered to the load should that prove to be necessary. 3) A liquid helium refrigerator is not required to cool the magnet down when a positive displacement pump is used, provided that one continuously fills the control dewar with liquid helium. The disadvantages of using a helium pump to supply helium to the magnet flow circuit are as follows: 1) The helium pump must be extremely reliable; reliability is an unproven issue for most positive displacement pump designs because they are subject to wear and tear. 2) If one pumps the helium through the flow circuit, pump work heat will be deposited in the helium being pumped.

Figure 2 illustrates two ways that the two-phase helium can be circulated on the coil support structure. The top of Fig. 2 illustrates the "Loop the Loop" flow path. This flow path is similar to the flow in a coiled hose hanging from a nail in the wall. The two-phase fluid flows up and down as it goes through the pipe. The flow circuit similar to that shown in upper part of Fig. 2 was used for the PEP-4 magnet[4] and the CLEO-1 magnet. The "Loop the Loop" flow circuit can be subject to "garden hose" oscillations if the helium tube is too large for the mass flow through the tube. The "Loop the Loop" flow circuit permits the magnet to cool down such that the cooing goes from one end of the magnet to the other. The bottom of Fig. 2 illustrates an alternative to the "Loop the Loop" flow system and its potential for "garden hose" oscillations. The "Back and Forth one turn around" flow path has only one garden hose loop so the potential for garden hose oscillations is greatly reduced. During magnet cool down, the temperature distribution in the coil is quite complex when the "Back and Forth" tube pattern is used. This type of flow pattern was used for the CELLO, TOPAZ, VENUS, CDF, DELPHI and W-2 magnets.[5] Both the "Loop the Loop" and the "Back and Forth" flow systems permit two-phase helium to be drawn off to cool the magnet gas cooled electrical leads. The orientation of these leads is immaterial provided that there is enough pressure to force gas through the leads.[6]

NATURAL CONVECTION TWO-PHASE COOLING

The alternative to forced two-phase flow in the tubes is natural convection in the cooling tubes around the magnet. Figure 3 illustrates the concept of how one would cool the STAR solenoid with natural convection. Liquid helium from a helium storage tank is fed into the bottom of the magnet through a liquid-helium manifold. The helium flows upward around the coil and boils to a two-phase gas-liquid manifold which then directs the helium to the gas space of the helium storage tank. The helium flow would behave like the flow up a coffee percolator, burping a two-phase mixture of gas and liquid back into the helium storage tank where phase separation occurs. This type of cooling system has been used for ALEPH and

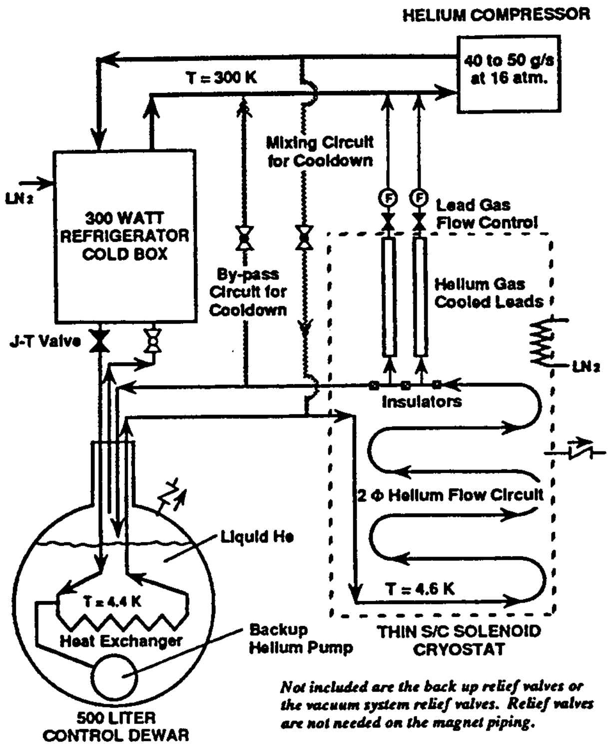

Fig. 1. Forced Two-phase Helium Cooling Using the Compressor to Circulate the Helium

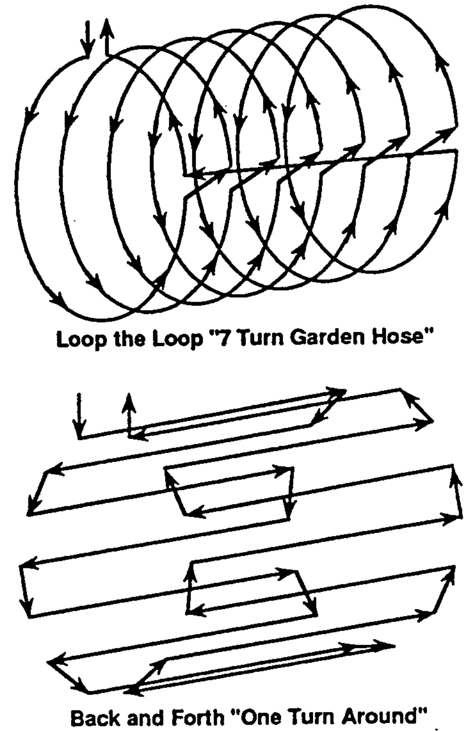

Fig. 2. Various Forced Two-phase Flow Options

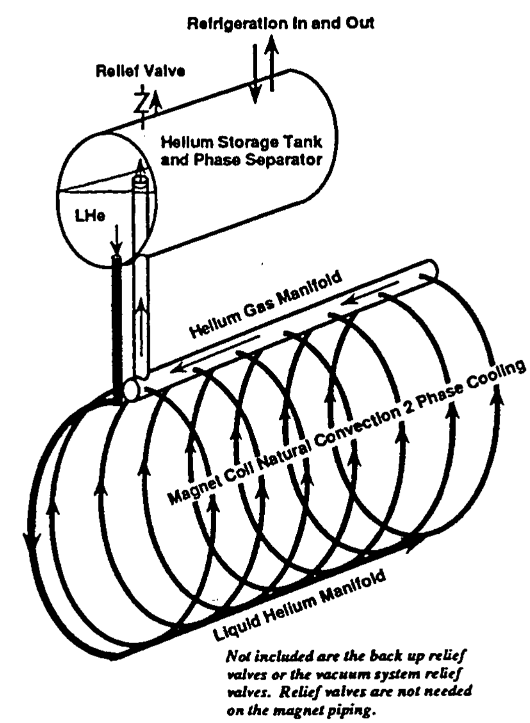

Fig. 3. Natural ConvectionTwo-phase Cooling

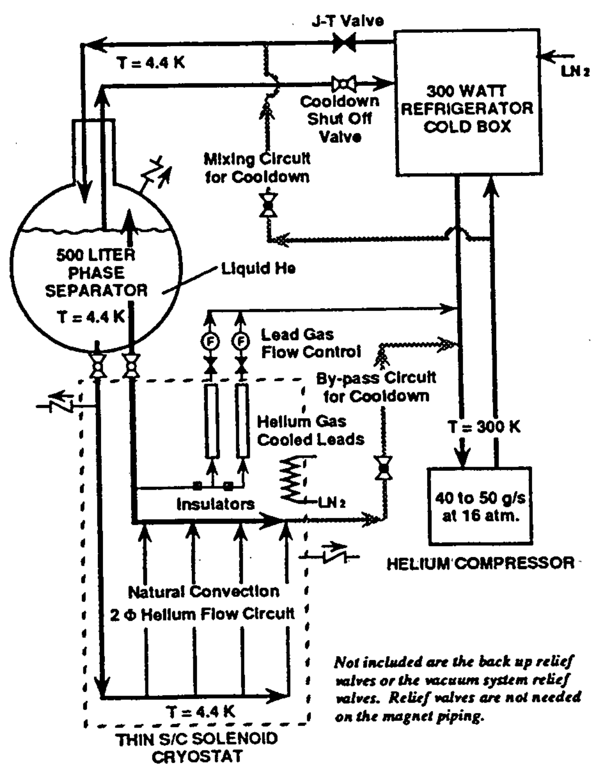

Fig. 4. Natural Convection Refrigeration Circuit

CLEO-2. This method of cooling has also been used for helium cooled cryogenic vacuum pumps for the fusion program. Figure 4 shows this method of cooling when the storage dewar is connected to a helium refrigerator.

The advantages of using a liquid helium tubular cooling system based on circulation by natural convection are as follows: 1) A natural convection cooling system will circulate helium in the magnet cooling tubes as long as there is liquid helium in the storage tank - phase separator. 2) The natural convection flow system will handle excess refrigeration required by the magnet as long as liquid remains in the helium storage tank and the flow tubes are not choked by boiling helium. 3) The temperature in the magnet cooling tubes is almost the same as the temperature of the helium bath in the helium storage tank - phase separator. 4) The phase separator insures that the helium will enter the magnet cooling liquid helium manifold at a quality very near zero. The disadvantages of circulating the helium in the magnet cooling tubes using natural convection are as follows: 1) The cold mass of the magnet and radiation thickness is somewhat larger when it is cooled by natural convection, particularly at the top and bottom of the magnet where the manifolds are located. 2) Cool down of the magnet is more difficult because the helium flows through the magnet through a number of parallel tubes. 3) The storage tank - phase separator must be located at an elevation above the gas manifold on the magnet. In some detectors, this can be a problem.

CONCLUSIONS

The use of forced two-phase helium cooling appears to be an attractive choice for the STAR magnet when it operates off of a 300 watt piston expander refrigerator. The pressure used to drive the two-phase cooling circuit should come from the helium refrigerator compressor. Natural convection magnet cooling is a viable alternative for the STAR solenoid. It is the best choice when the magnet is operated with liquid helium from a liquefier (the helium is returned to the liquefier as a gas) or when the compressor is subject to shut down by power glitches. Natural convection cooling is less flexible in terms of storage tank placement and the point at which the transfer lines enter the magnet, but the STAR magnet will continue to operate off of helium in the storage tank when the refrigerator or its compressor cease to operate. It is clear that before the STAR magnet cryostat can be specified, the type helium cooling system must be agreed upon.

ACKNOWLEDGEMENTS

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